**Economical Mixtures to Reduce Both Thermal and Autogenous Shrinkage Contributions
to Early-Age Cracking**

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Abstract

Early-age cracking continues to be a significant problem for new concrete construction. Two of the major contributors to such cracking are the heat released by cement hydration during the first few days of curing and the autogenous shrinkage that often occurs during the same timeframe. In this paper, three potential alternatives for reducing these contributions by modifying the concrete mixture proportions are investigated, namely increasing the water-to-cement ratio, utilizing a coarser cement, or replacing a portion of the portland cement with a coarse limestone powder. Each alternative reduces the heat generated per unit volume by either reducing the volumetric cement content or its early-age reactivity, and reduces autogenous shrinkage by increasing the interparticle spacing between grains in the three-dimensional microstructure. These reductions are quantified for paste and mortar systems by measuring their semi-adiabatic temperature rise and autogenous deformation, along with measurements of compressive strength to indicate the strength tradeoff that will be experienced in reducing the risk of early-age cracking. These mixtures each have the additional advantage that they should result in a cost savings in comparison to an initial (control) mixture.

Keywords: Autogenous deformation; building technology; early-age cracking; mixture proportioning; thermal stresses.

Introduction

Despite efforts to avoid it, many concrete structures crack, often at early ages.[1] In fact, for a variety of reasons, high-performance concretes are often more susceptible to early age cracking than the concretes that were placed fifty years ago.[2] These reasons include their typically higher cement contents, the use of finer (and finer) cements with higher tricalcium silicate and alkali contents, and the formation of a denser paste matrix via the reduction of water-to-cementitious materials ratio (*w/cm*) and the addition of fine pozzolans such as silica fume.[3,4] One indication of the magnitude of the early-age cracking problem is that there are now viable mitigation strategies that are being actively marketed by chemical admixture, lightweight aggregate, and specialty cement suppliers. Such strategies include the utilization of a shrinkage-reducing admixture (SRA) to reduce autogenous shrinkage,[5,6] the incorporation of internal curing via pre-wetted lightweight aggregates,[7] and the use of expansive cements.[8] Each of these strategies reduces autogenous shrinkage and may even result in an autogenous expansion at early ages, but none of them directly addresses the heat released by hydration that will lead to a temperature rise and fall that may exacerbate early-age cracking. For example, internal curing

may actually increase early-age hydration rates thus increasing this heat release, but fortunately, the additional thermal (heat) capacity of the internal curing water may reduce the temperature rise produced by a given amount of heat release. Additionally, each of these three technically viable solutions will generally increase the cost of the concrete mixture.

Two key physical parameters influencing the heat generation and autogenous deformation of cement pastes are surface area and interparticle spacing. Early-age reactivity and heat release will generally be proportional to the former, while the latter will control the size of the pores emptied (and thus the stresses generated) during the early-age self-desiccation that may occur due to the chemical shrinkage that accompanies the cement hydration reactions.[9] While SRAs reduce autogenous shrinkage by lowering the surface tension of the pore solution and internal curing provides mitigation by avoiding self-desiccation of the hydrating cement paste as the larger pores in the lightweight aggregate reservoirs empty instead, a third approach to decreasing early-age cracking susceptibility would be to modify the physical geometry of the initial cement paste microstructure. In this paper, three distinct methods for "coarsening" the initial spatial distribution of cement particles will be investigated, namely the use of a coarser ground cement, an increase in the water-to-cement mass ratio (w/c), and the replacement of a fraction of the cement by a (coarse) limestone powder. To conserve cement and energy, the ASTM C150 Standard Specification for Portland Cement[10] currently permits a 5 % limestone addition to portland cement, and the Canadian Standards Association is considering raising this value to 10 % or 15 %. It will be shown that each of these three methods can reduce both the thermal and autogenous deformation contributions to early-age cracking. In addition, each of these should potentially offer a cost advantage over the control mixture that is being modified. It is recognized that there are other viable approaches to achieve the goals of cost reduction concurrent with reduced early-age cracking, such as the development of high-volume fly ash concretes for sustainable development.[11]

Research Significance

While concretes are designed to meet strength requirements and to promote long term durability of concrete structures, both of these can be compromised if the concrete cracks at early ages. Early-age cracking is a complex process that depends on materials, construction practices, structural loads, and environmental conditions.[12] The potential of a given concrete mixture for such cracking can be analyzed by measurement of a variety of early-age properties such as (semi)adiabatic temperature rise and autogenous deformation.[12,13] When a mixture exhibits a "high" potential for such cracking, modifications to its mixture proportions may be required to reduce this potential. In this paper, three such modifications that focus on modifying the surface area and interparticle spacing of the particles comprising the cementitious matrix component of the concrete are quantitatively examined. Each modification also has the potential to reduce the materials cost of the concrete. The results will provide guidance to designers in making the necessary modifications to reduce the probability of early-age cracking of a given concrete mixture.

Experimental

Two Type I/II cements of widely different fineness were obtained from Lehigh Portland Cement Co. and two limestone powders (94 % $CaCO_3$) were obtained from OMYA, a calcium carbonate supplier.[A] The chemical and physical characteristics of the cements are summarized in Table 1. They are quite similar in chemical composition except for the coarser cement having a lower total alkali content. The measured particle size distributions of all four powders are provided in Figure 1. A specific gravity of 2.71, as supplied by the manufacturer, was used for the limestone in proportioning the mortar mixtures.

Table 1. Cement oxide compositions, Bogue potential phase mass fractions,[10] and fineness.

Oxide or property	Fine cement	Coarse cement
CaO	0.633	0.648
SiO_2	0.203	0.209
Al_2O_3	0.045	0.045
Fe_2O_3	0.0339	0.041
SO_3	0.0268	0.022
Na_2O	0.00077	0.003 (equiv.)
K_2O	0.00622	Not reported
MgO	0.0373	0.012
P_2O_5	0.00127	Not reported
TiO_2	0.00309	Not reported
Bogue - C_4AF	0.103	0.125
Bogue - C_3A	0.062	0.050
Bogue - C_3S	0.625	0.625
Bogue - C_2S	0.109	0.127
Specific gravity	3.22	3.21
Fineness (Blaine)	380 m^2/kg	311 m^2/kg

For this study, specimens prepared using the finer cement with a *w/c* = 0.35 were selected as the control system. Several possible variations from this control were investigated to quantify their effects on strength development, semi-adiabatic temperature rise, and autogenous deformation. These included the substitution of the coarser cement for the finer one, an increase in *w/c* to 0.4 for the fine cement, and replacing a portion of the fine cement with either a fine or a coarse limestone. Due to the differences in specific gravity between limestone and cement, the limestone replacement was conducted so as to maintain the same volumetric ratio of water to solid powders in the various mixtures. Thus, a 10.2 % replacement by mass (about 12 % by volume) of limestone for cement and a water-to-cementitious materials mass ratio (*w/cm*) of 0.357 were employed for the two systems with either fine or coarse limestone replacement for cement, giving an effective *w/c* (not considering the limestone) of about 0.4 for these mixtures.

[A] Certain commercial products are identified in this paper to specify the materials used and procedures employed. In no case does such identification imply endorsement by the National Institute of Standards and Technology, nor does it indicate that the products are necessarily the best available for the purpose.
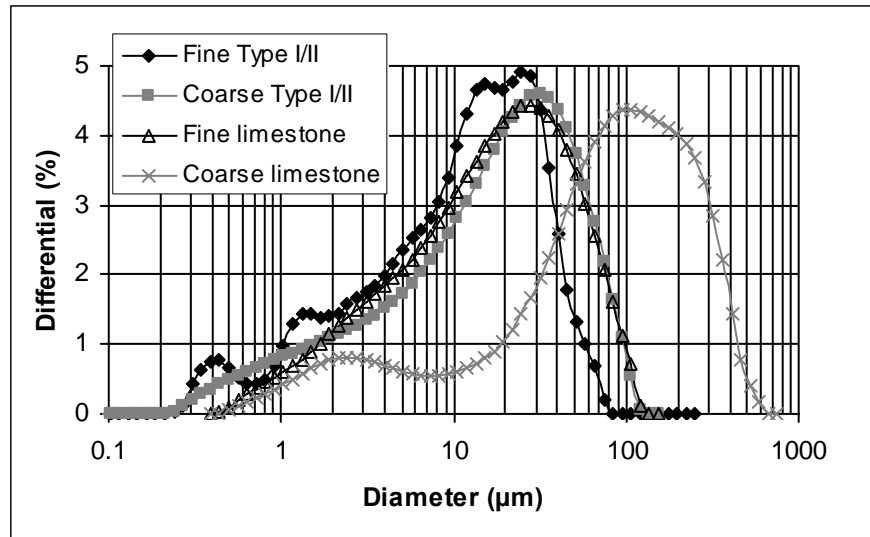
Figure 1. Measured differential particle size distributions for the various materials used in the study. (One micrometer is equivalent to 3.9×10^{-5} in.)

Semi-adiabatic calorimetry studies were conducted on cement paste specimens during the course of 3 d hydration, using a custom-built experimental setup.[14] The pastes were prepared using a high speed blender and immediately cast into a cylindrical plastic mold with an inner diameter of 47 mm (1.85 in) and a height of 97 mm (3.8 in). A typical sample mass was about 330 g (0.73 lb). The filled mold was immediately placed in an insulative holder (constructed of microporous insulation) and a single Type J thermocouple inserted into the center of the paste volume. This temperature, along with the room temperature, was then monitored during the course of several days of semi-adiabatic hydration. Replicate specimens have indicated a standard deviation of 1.4 °C in the maximum specimen temperature achieved during this period.

For the evaluation of compressive strength and autogenous deformation, mortar mixtures were prepared following the proportions provided in Table 2. For the various mortars, the same volume fraction of sand (54.8 %) was maintained in each mortar mixture. Thus, for this study, the limestone is being considered as part of the cement paste and not as part of the aggregates in the mortar for the purposes of mixture proportioning. A blend of four normal weight sands (specific gravity = 2.61) that has been shown to provide improved particle packing for high-performance mortars was employed in all mortar mixtures. Mixing of the mortars was conducted according to ASTM C305.[15]

Autogenous deformation was assessed using the sealed corrugated tubes as developed by Jensen and Hansen.[17] In most cases, three replicate specimens were evaluated concurrently. For each mortar mixture, the autogenous deformation measurements were "zeroed" at the following times, based on measurement of the final (Vicat) setting times of cement paste specimens of the same w/c[13]: 4 h for the $w/c = 0.35$ coarse cement mortar, 5 h for the $w/c = 0.35$ fine cement mortar, and 6 h for the $w/c = 0.4$ fine cement mortar and both mortars with limestone replacements (effective $w/c = 0.4$). By definition, autogenous deformation should be measured under isothermal conditions and such conditions are being assumed for the corrugated tubes employed in this study. In reality, as stated in the draft ASTM standard being developed for this

4

1 technique, "Typical maximum temperature increase in the center of the test specimen, due to
2 heat of hydration of cement paste or mortar, is 2°C."
3
4 Table 2. Mortar mixture proportions used in the study.

Material	w/c = 0.35 (fine & coarse cement)	w/c = 0.4 (fine)	w/cm = 0.357 (fine cement with limestone)
Type I/II cement	1860.5 g (4.10 lb)	1757.3 g (3.87 lb)	1544.2 g (3.40 lb)
Limestone	0.0 g (0.0 lb)	0.0 g (0.0 lb)	175.5 g (0.39 lb)
Water	651.2 g (1.43 lb)	702.9 g (1.55 lb)	614.2 g (1.35 lb)
F95 fine sand[A]	972.1 g (2.14 lb)	985.0 g (2.17 lb)	916.5 g (2.02 lb)
Graded sand (ASTM C 778[16])	738.8 g (1.63 lb)	748.6 g (1.65 lb)	696.6 g (1.53 lb)
20-30 sand (ASTM C 778[16])	738.8 g (1.63 lb)	748.6 g (1.65 lb)	696.6 g (1.53 lb)
GS16 coarse sand[A]	1438.7 g (3.17 lb)	1457.7 g (3.21 lb)	1356.5 g (2.99 lb)

5 [A]F95 and GS16 correspond to sand supplier designations.
6
7   Compressive strength testing was conducted on 50 mm (2 in) mortar cubes at the ages of
8 1 d, 3 d, 7 d, and 28 d. The cubes in their molds were stored in double sealed plastic bags during
9 the first 24 h of curing, demolded, and placed in saturated limewater until the time of testing.
10 The mass of each cube was measured upon demolding and just prior to compressive strength
11 testing.   Curing and measurements of autogenous deformation were conducted at a temperature
12 of 25 ± 1 °C (77 ± 2 °F), as maintained in a walk-in environmental chamber.
13
14 **Results and Discussion**
15
16 *Initial Paste Microstructures*
17
18   To provide a specific image of how surface area and interparticle spacing vary amongst
19 the mixtures examined in this study, three-dimensional simulations of the starting
20 microstructures of four of the paste mixtures were conducted using digitized spherical particles
21 and a simulation volume of 100 μm x 100 μm x 100 μm (0.0039 in x 0.0039 in x 0.0039 in).[13]
22 Sample two-dimensional slices from the four systems are provided in Figure 2. The coarse
23 w/c = 0.35 cement system (Figure 2b) is seen to have the largest interparticle spacing, followed
24 by the fine w/c = 0.4 cement system (2c), the w/cm = 0.357 system with fine limestone (2d), and
25 finally by the fine w/c = 0.35 cement paste (2a). Since the effective w/c in the systems with
26 limestone replacement is about 0.4, the spacing in the system with the coarser limestone filler
27 (not shown in Figure 2) would be expected to be similar to that of Figure 2c, assuming that the
28 "cement paste" occupies space between the relatively larger limestone particles and neglecting
29 any interfacial transition zones that may form around the larger limestone particles.
30
31 *Compressive Strengths*
32
33   The compressive strength testing results are summarized in Table 3 and a relative
34 comparison to the control system is provided in Figure 3.   In every case, the mixture
35 modifications performed to coarsen the pore structure resulted in substantial decreases in the 1 d
36 strength values. Depending on the modification, the observed decrease in strength at early ages
37 could be due to one or more of the following reasons: an increase in porosity (w/c = 0.4 vs.
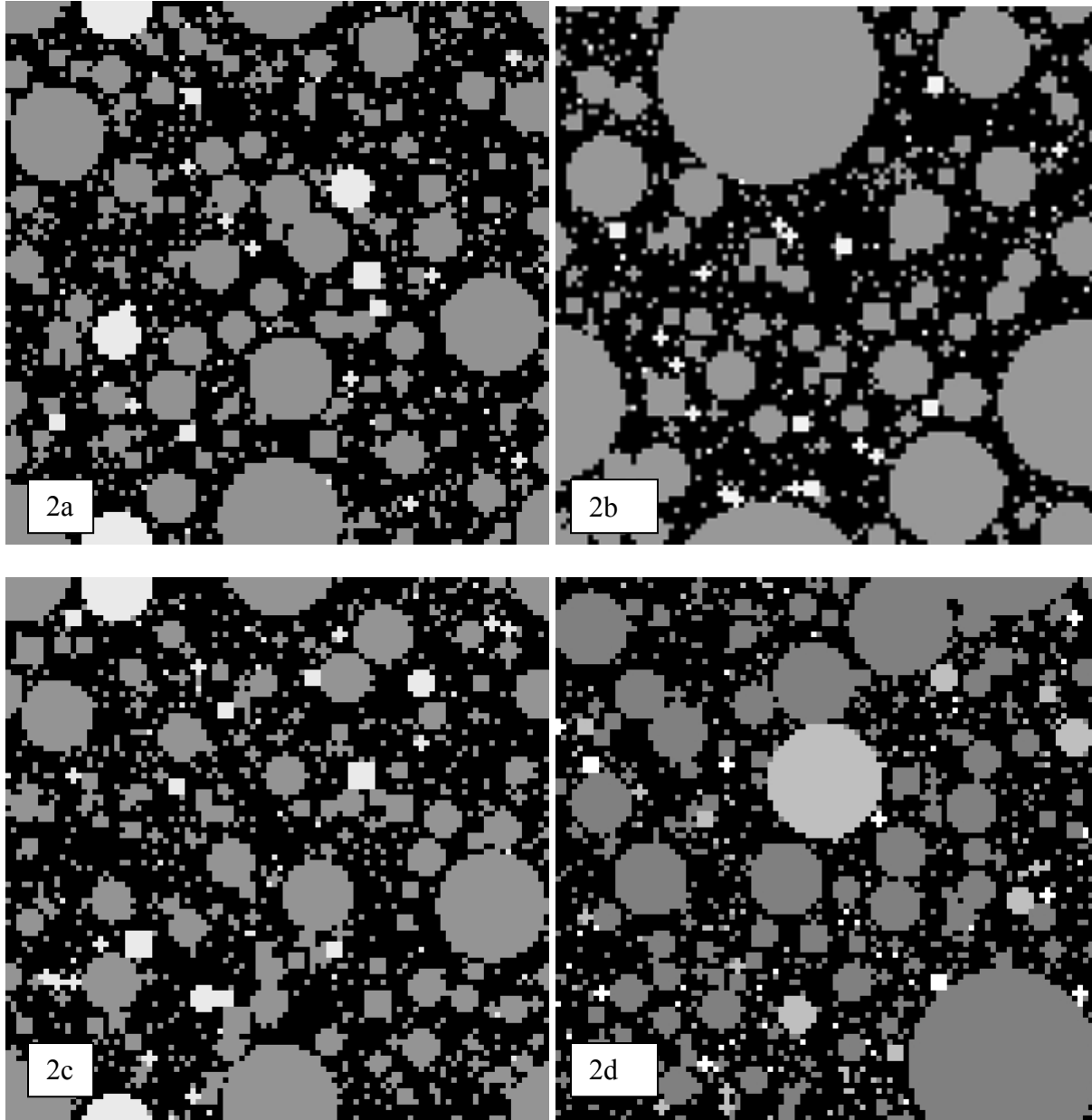
Figure 2. Two-dimensional slices (100 μm x 100 μm or 0.0039 in x 0.0039 in) from simulated three-dimensional starting paste microstructures for the various mixtures. Bright particles are gypsum, dark grey particles are cement, and light grey particles are limestone (in 2d). Water-filled porosity is black. Microstructures are for a) $w/c = 0.35$ fine cement, b) $w/c = 0.35$ coarse cement, c) $w/c = 0.4$ fine cement, and d) $w/cm = 0.357$ fine cement with fine limestone replacement.

$w/c = 0.35$ for instance), a decrease in hydration product formation either due to a decreased cement content (systems with limestone replacement) or a decreased cement surface area (coarser cement), or an increase in average pore size (all modified systems).

Of course, it is well known that compressive strength will decrease with an increase in w/c. Still, it is interesting to note that while the 1 d strength of the $w/c = 0.4$ mortar is only 70 %

1 of that of the *w/c* = 0.35 mortar, by 28 d, a strength that is 93 % of the control mortar is achieved.
2 One may be willing to trade off such a loss in 28 d compressive strength, if the semi-adiabatic
3 temperature rise and autogenous shrinkage are substantially reduced in the higher *w/c* concrete.
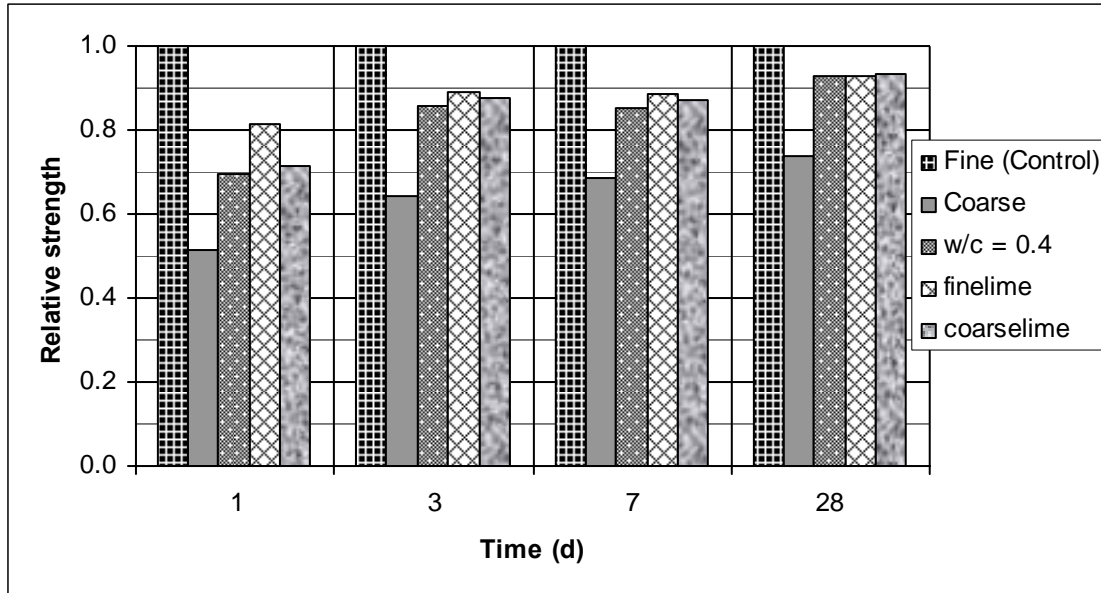4

6 Figure 3. Relative strength values for the various mortar mixtures.

8   The use of coarser cements in high-performance concretes has been suggested previously
9 due to the fact that in these generally low *w/cm* concretes, only a fraction of the cement has space
10 to hydrate.[18] Thus, the same long term degrees of hydration (and strengths) may be achieved via
11 a coarse cement as via a finer one. Previously, simulations had indicated the same long term
12 (160 d) degree of hydration for coarse and fine cements for *w/c* = 0.246 and similar values for
13 *w/c* = 0.3.[18] However, the experimental results in this study indicate that for *w/c* = 0.35, while the
14 coarser cement improves from having 51 % of the 1 d strength of the control (fine cement)
15 system to having 74 % of its 28 d strength, the coarser cement will likely not achieve a totally
16 equivalent strength even at longer ages. However, coarser cements may offer other benefits such
17 as the increased durability of concretes produced with coarser cements as pointed out by Brewer
18 and Burrows over 50 years ago[2] and a reduced autogenous deformation as to be presented
19 subsequently.
20

21   In low *w/cm* concretes, an even greater potential exists to conserve cement and energy by
22 replacing the coarsest cement particles with limestone powder.[19-21] In this study, the influence of
23 the fineness of the limestone was examined by replacing about 10 % of the cement by mass with
24 either a fine or a coarse limestone (Figure 1). Considering strength, the replacement by the fine
25 limestone particles offers a superior performance at 1 d, perhaps due to its smaller initial
26 interparticle spacing (Figure 2d vs. 2c). While the initial acceleration of the cement hydration
27 reactions by limestone can be dependent on the limestone powder's surface area,[22,23] isothermal
28 calorimetry[13] results indicated basically identical heat flow vs. time curves for the first 24 h of
29 hydration for both *w/cm* = 0.357 pastes with fine or coarse limestone replacements for cement.
30 Thus, it appears that the greater strength produced at 1 d by the mortar with the fine limestone
31 replacement is not due to acceleration of the cement hydration reactions in this case, but rather

1   Table 3. Compressive strength results for mortar cubes.

Mixture	1 d strength (MPa/psi)	3 d strength (MPa/psi)	7 d strength (MPa/psi)	28 d strength (MPa/psi)
w/c = 0.35 fine cement	36.2 (1.4)^B / 5250	55.6 (2.4) / 8070	64.8 (1.0) / 9390	78.5 (2.2) / 11380
w/c = 0.35 coarse cem	18.5 (1.2) / 2690	35.8 (3.1) / 5190	44.4 (2.4) / 6450	58.0 (3.5) / 8410
w/c = 0.4 fine cem	25.2 (0.4) / 3650	47.6 (1.5) / 6910	55.1 (1.6) / 8000	72.8 (1.4) / 10560
w/cm = 0.357 fine cem/ fine limestone	29.5 (1.0) / 4280	49.4 (2.7) / 7170	57.4 (0.2) / 8320	72.9 (3.9) / 10580
w/cm = 0.357 fine cem/ coarse limestone	25.8 (1.0) / 3750	48.8 (1.1) / 7080	56.4 (3.0) / 8180	73.3 (3.4) / 10630

2   ^{B}Numbers in parentheses indicate one standard deviation in MPa as determined for the three replicate specimens tested at each age.

due to smaller pores between the initial cement and limestone particles. Beyond 1 d, the coarser limestone system produces nearly equivalent strengths by 3 d, and by 28 d, the measured strengths are essentially equal within experimental uncertainty. Due to its initially coarser pore structure, the mortar cubes with the coarser limestone are able to imbibe more external curing water to promote long term strength gain. For example, at 3 d, the cubes containing the finer limestone had imbibed 0.017 kg of water per kg of cement (0.017 lb of water per lb of cement) while those containing the coarser limestone had imbibed 0.027 kg of water per kg of cement (0.027 lb of water per lb of cement), almost a 60 % increase. As shown in Table 3, with their effective *w/c* of 0.4, the two systems with limestone replacement for cement exhibit 28 d strengths that are basically equivalent to that of the pure portland cement *w/c* = 0.4 mortar. However, while the two mortars with limestone replacements exhibit similar 28 d strengths, as will be shown in the results to follow, limestone fineness also has an influence on the semi-adiabatic temperature rise and particularly on the measured autogenous deformation of mortars.

Semi-adiabatic Temperature Rise

The semi-adiabatic temperature rise curves are provided in Figure 4 and the maximum temperatures recorded for each mixture are included in Table 4. Each of the modified mixtures is observed to significantly reduce the maximum temperature achieved during the early-age hydration. Because the *w/c* = 0.4 cement paste has an increased heat capacity relative to the other mixtures and can maintain a higher rate of hydration at later ages, both of these being due to its higher volume fraction of water, it shifts the temperature maximum to a later time by about 2 h. The maximum temperature is also shifted somewhat for the coarser cement, but in this case, it is caused by this cement's lower early-age reactivity due to the coarser particles and a reduction in (reactive) surface area. Conversely, the systems with limestone exhibit their temperature maximums only slightly later than the control system. While these systems have the same volume fraction of water as the control system, and thus a similar heat capacity, they do have less cement per unit volume generating heat and relatively more space for the precipitation of hydration products in comparison to the control system. The results in Table 4 indicate that the mixture based on the coarser cement has over double the maximum temperature reduction (relative to ambient) as the mixtures based on a higher *w/c* or limestone replacements. Of course, this reduction comes at the expense of early-age strength and it is interesting to note that for the five mixtures examined in this study, there is a reasonably linear relationship ($r^2 = 0.9$) between the maximum temperature observed in the semi-adiabatic testing and the 1 d compressive strengths provided in Table 3. While this relationship would likely not be maintained across other mixtures, certainly, in general, more energy released by cement hydration will imply a greater degree of hydration (and thus strength) and an increased semi-adiabatic temperature rise.

Autogenous Deformation

The plots of autogenous deformation in Figures 5 and 6 show the results out to 7 d and 28 d, respectively. While reductions in the autogenous shrinkage as compared to the control *w/c* = 0.35 mortar, which is based on the fine cement, are exhibited by all of the modified systems except for the one incorporating the fine limestone replacement for cement, a wide variation is observed in their specific performances. The mortar with an increased *w/c* exhibits an early-age autogenous expansion with an overall deformation of -80 microstrains at 26 d.

Table 4. Maximum temperature achieved in semi-adiabatic testing and (ε_{min}-ε_{max}) at 7 d for cement pastes and mortars, respectively.

| Cement paste or mortar	Maximum temperature (% Reduction vs. control)	(ε_{min}-ε_{max}) at 7 d and (% Reduction vs. control)
w/c = 0.35 fine cement	66.9 °C (153 °F) (---)	-127 microstrains (---)
w/c = 0.35 coarse cement	47.4 °C (117 °F) (43 %)	-49 microstrains (61 %)
w/c = 0.4 fine cement	59.8 °C (140 °F) (16 %)	-100 microstrains (21 %)
w/cm = 0.357 fine cement/fine limestone	58.8 °C (138 °F) (18 %)	-163 microstrains (-28 %)
w/cm = 0.357 fine cement/coarse limestone	57.8 °C (136 °F) (20 %)	-88 microstrains (31 %)
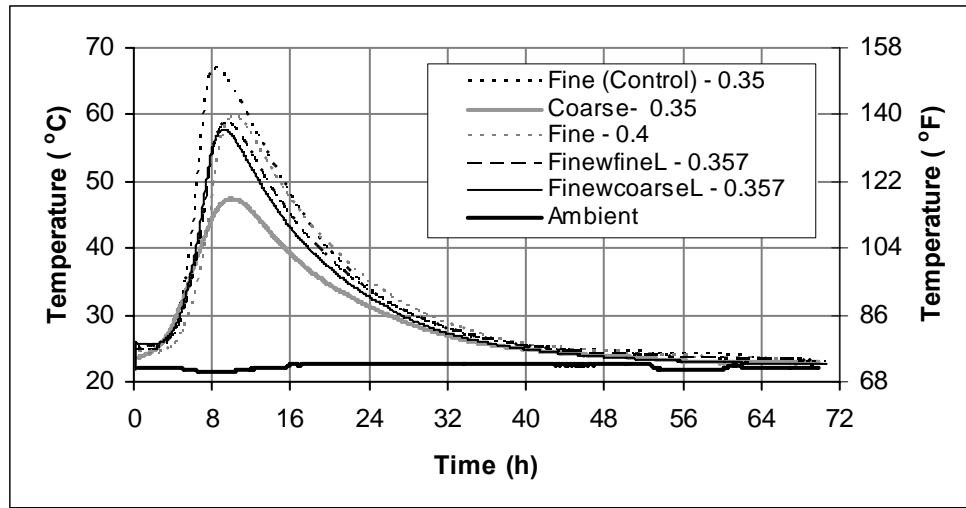
Figure 4. Semi-adiabatic temperature rise vs. time for the various cement pastes.

Autogenous deformation is always a competition between autogenous shrinkage due to self-desiccation and autogenous expansion due to some aspects of the cement hydration reactions that produce swelling at early ages (perhaps ettringite formation, the growth of calcium hydroxide crystals, and/or imbibition of water by the gel hydration products).[9,24] For a given cement fineness and mortar proportions, there will be a threshold w/c below which autogenous shrinkage will dominate and above which an overall expansion (at 28 d for instance) will be measured.[24,25] For the finer cement used in this study, this threshold is seen to be above 0.4, while for the coarser cement, based on the results in Figures 5 and 6, it is somewhat less than 0.35, as the w/c = 0.35 coarser cement mortar still exhibited an overall deformation of 50 microstrains (expansion) after 28 d of sealed curing.

The autogenous deformation results for the two systems with limestone replacements for cement are particularly interesting. As shown in Figure 2, the system with the fine limestone powder produces a microstructure with similar initial pore "sizes" to that of the control mortar. In this case, no improvement in autogenous deformation is observed. The results in Figures 5 and 6 indicate that following a slight difference in their initial expansions, the system with the fine limestone replacement produces an autogenous deformation curve that is basically parallel to that of the control w/c = 0.35 mortar. Any differences between these two curves could be well
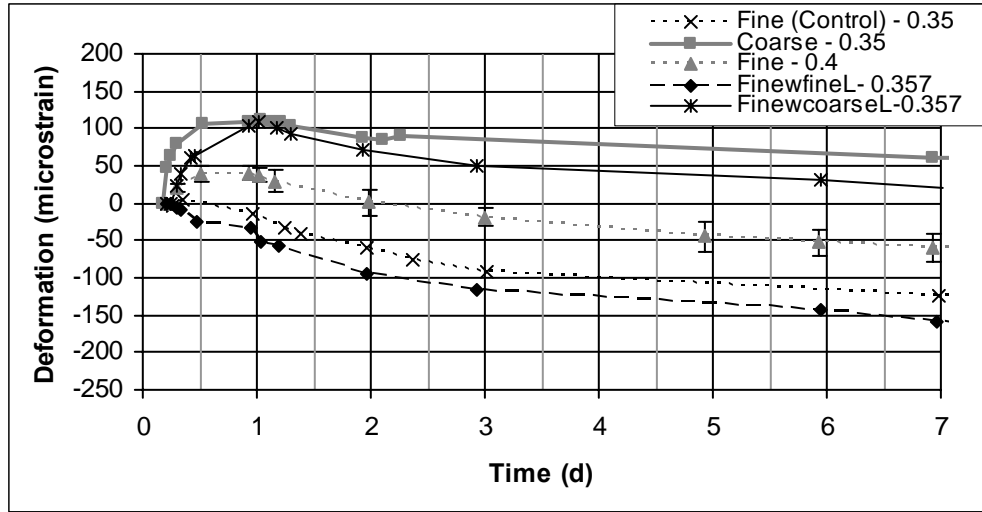
Figure 5. Autogenous deformation vs. time for the first 7 d for the mortar mixtures. Error bars shown on the fine 0.4 curve indicate a typical standard deviation for replicate specimens.
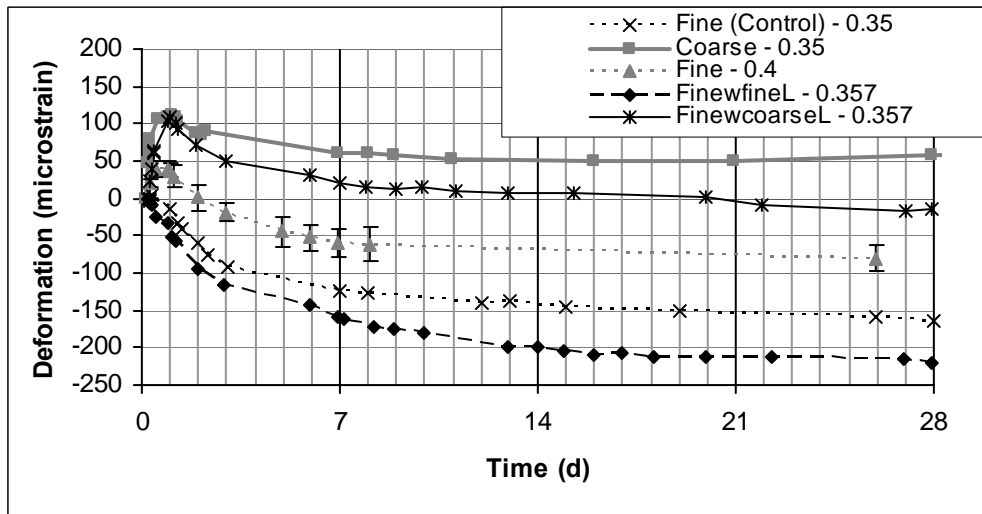

Figure 6. Autogenous deformation vs. time for 28 d for the mortar mixtures.

within the measurement variability and/or partially due to the fact that their autogenous deformations were "zeroed" at slightly different times, 5 h for the control mortar and 6 h for the mortar with fine limestone replacement. Conversely, the results for the coarse limestone powder replacement are seen to be quite different from those with fine limestone, exhibiting a significant expansion to an age of 1 d and then an autogenous shrinkage, with an overall deformation of about -15 microstrains after 28 d. It was mentioned earlier that the spacing between cement particles in this system might be similar to that in the $w/c = 0.4$ fine cement system and indeed, after their initial expansions reach some (different) maximum values, these two systems exhibit basically parallel curves for the (relative) shrinkage portions of their autogenous deformation.

It is unknown at this time why the initial autogenous expansion of the mortar with the coarse limestone replacement is so much larger than that observed in the other mortars using the fine cement. Possibilities could include the formation of large expansive crystals of calcium

11

hydroxide[24] and/or ettringite and carboaluminate hydration products (as recently observed by Sato and Beaudoin in systems with nano-limestone additions[23]) leading to an enhanced expansion, or perhaps a more uniform distribution of gel hydration products on both the cement and limestone grains leading to a greater expansion of the paste during water imbibition by this gel. The system with the finer limestone replacement, with its smaller initial pore sizes, might not provide sufficient space for the formation of such large crystals and any enhanced expansion of the gel hydration products could be offset by the large shrinkage strains generated as these much smaller pores empty during self-desiccation in this system (Figure 2d).

Recently, Cusson has advocated the utilization of the (net) difference between the maximum (peak) and minimum (post peak) deformations achieved during the first 7 d of curing as an effective measure of the risk of cracking in a concrete structure, as a concrete typically reaches a zero-stress state sometime after the peak (expansion) is achieved, but prior to the autogenous deformation returning to zero (or achieving its minimum value).[26] Beyond this zero-stress time, tensile stresses develop and build and may ultimately lead to early-age cracking if the tensile strength of the concrete is exceeded at any time.[12,26] For the five mixtures examined in this study, these values of net autogenous shrinkage, $(\varepsilon_{min}-\varepsilon_{max})$, are provided in Table 4. In terms of this performance parameter, the ranking of the mixtures would be: 1) the coarser cement with $w/c = 0.35$, 2) the fine cement with the coarse limestone replacement, 3) the fine cement with $w/c = 0.4$, 4) the fine cement with $w/c = 0.35$, and 5) the fine cement with the fine limestone replacement. If this performance criteria were considered to be the critical measure for autogenous deformation contributions to early-age cracking, as indicated in Table 4, the coarser cement would provide the best performance for reducing both the thermal and autogenous deformation contributions to early-age cracking.

It is important to note that the results with the coarse limestone replacement presented in this paper have been obtained by blending a coarser limestone powder with a finer cement. Such a distribution of these two materials, for instance, would be unlikely to be obtained by intergrinding a softer limestone with a harder cement clinker, a procedure that is often currently employed within the cement industry. The coarser limestone contributes to an increase in the initial interparticle spacing of the blended cement that reduces the autogenous deformation at early ages, while not dramatically impacting 28 d strength.

Potential Costs and Durability

It is always important to consider the cost implications of any modifications to mixture proportions, since unit costs are the bottom line that drives much of construction today. Fortunately, in this case, it is projected that each of these three different mixture modifications will result in a materials cost reduction. For example, by increasing w/c from 0.35 to 0.4 at a fixed paste volume fraction, the volume of cement utilized will be reduced by 7 %. As cement is generally the most expensive component of the concrete mixture (neglecting admixture costs), the overall concrete cost should be reduced by at least several percent. While the utilization of a coarser cement doesn't in itself reduce cement consumption, it should reduce the energy costs involved in grinding the cement to the needed fineness. As indicated earlier, the mixtures with limestone replacement will result in a 12 % reduction in the volume of cement per unit volume of concrete, and may potentially offer the largest cost savings, depending on the cost of the

limestone powder. And, of course, if these mixture modifications reduce early-age cracking, leading to an increase in concrete durability, the life-cycle costs of any concrete structures produced with these mixtures could be dramatically reduced.

Still, it is natural to question what will be the long term durability implications of these mixture modifications. While there is no question that each of the modifications is "coarsening" the early-age pore structure and that a coarser pore structure often implies lower durability due to higher transport rates, the "ultimate" pore structures of these mixtures achieved at and beyond 28 days of hydration could be quite similar, as exemplified by the convergence of their 28 d compressive strengths. While one frowns (and some even cringe) upon using strength as a durability measure, most durability properties do exhibit a very good correlation to strength for mixtures that do not vary too widely.[27] Thus, if equivalent or nearly equivalent strengths are achieved at 28 d for these mixtures with relatively minor modifications from the control systems, equivalent durability might be expected. Of course, one must keep in mind chemical issues specific to the materials being employed, such as the thaumasite form of sulfate attack[28,29] in the systems containing limestone replacements for cement.

There has always been and will continue to be a delicate balance between early-age strength development and the likelihood of early-age cracking.[30] Currently, the pendulum has perhaps swung too far in the direction of high early-age strengths. The mixture modifications examined in this study can hopefully assist in moving it back towards center with equal emphasis on strength and early-age cracking.

Conclusions

High early-age strength often correlates with a high semi-adiabatic temperature rise and an increased autogenous shrinkage. By modifying the initial geometry of the cement particles, specifically their surface area and interparticle spacing, both of these contributions to early-age cracking can be reduced. Three possible modifications are an increase in *w/c*, the utilization of a coarser cement, or the replacement of part of the cement by a coarse limestone powder. While these modifications do reduce early-age strength significantly, in several cases, the reduction in 28 d strength is below 10 %. The coarser cement offers the largest benefit in terms of reducing semi-adiabatic temperature rise and effective autogenous shrinkage at 7 d, but also produces the lowest strength mortars at all ages tested. The replacement of about 10 % by mass of the cement by a coarse limestone produced a mortar with an overall autogenous deformation near zero at 28 d and a net autogenous shrinkage of -88 microstrains at 7 d ,and may be the most economical and sustainable of the three modifications. An increase in *w/c* reduced both autogenous shrinkage and semi-adiabatic temperature rise and can be easily achieved without obtaining any additional materials.

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